Neutron Backgrounds in Coherent Neutrino-Nucleus Scattering Experiments

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Outline

- What is coherent neutrino scattering?

- How can we look for it at FNAL?

- Detector design for coherent neutrino scattering experiment

- Why is neutron shielding necessary?

- Development of simulation to estimate the amount of neutron shielding needed

Coherent-NCvAS

▶ A coherent scattering process is, generally, one in which the momentum transfer is low enough that the wavefunctions of the target remain coherent and in phase.

▶ A coherent elastic neutrino nucleus scattering process is a consequence of the existence of a neutral current. Coherent-NCvAS was predicted by Freedman (1974) [1], but it has never been observed.

The process is mediated by the exchange of a Z^0 vector boson and the cross section does not depend on the flavor of the incident neutrino.
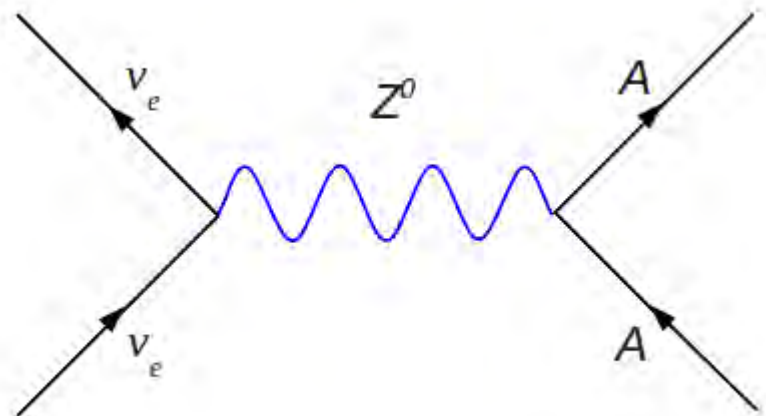
Coherent-NCvAS

▶ Standard model cross section for coherent-NCvAS in the zero momentum transfer limit is given by:

$$\sigma_{\nu N} \simeq \frac{4}{\pi} E_\nu^2 [Z\omega_p + (A - Z)\omega_n]^2$$

$$\omega_p = \frac{G_F}{4}(4\sin^2\theta_W - 1), \quad w_n = \frac{G_F}{4}$$

▶ Since $\sin^2\theta_W = 0.23$, the coupling of the Z^0 to the proton is suppressed and the cross section scales with $(A\text{-}Z)^2$.

Similar to the A^2 scaling of some particle dark matter candidates (e.g., neutralinos)

Coherent-NCvAS

▶ The conditions for coherence, for nuclei in most detector materials, require that:

$$E_\nu < \frac{1}{R_N} \simeq 50 \text{ MeV}$$

▶ The cross section for coherent-NCvAS at this energy is:

$$\sigma_{\nu N} \simeq 10^{-39} cm^2$$

▶ Compare to ~10^{-40} cm^2 for charged-current inverse β decay and ~10^{-43} cm^2 elastic neutral-current neutrino-electron scattering.

Coherent-NCvAs

▶ In addition to the simple fact that it remains undiscovered, coherent-NCvAs is of interest for a number of reasons.

▶ Coherent-NCvAs is an irreducible background in next-generation dark matter experiments.

▶ It also plays an important role in stellar collapse [2].

▶ Finally, deviations from the Standard Model cross section could be a signal of new physics.

Experimental Limits on WIMP (Weakly Interacting Massive Particle) Cross Sections
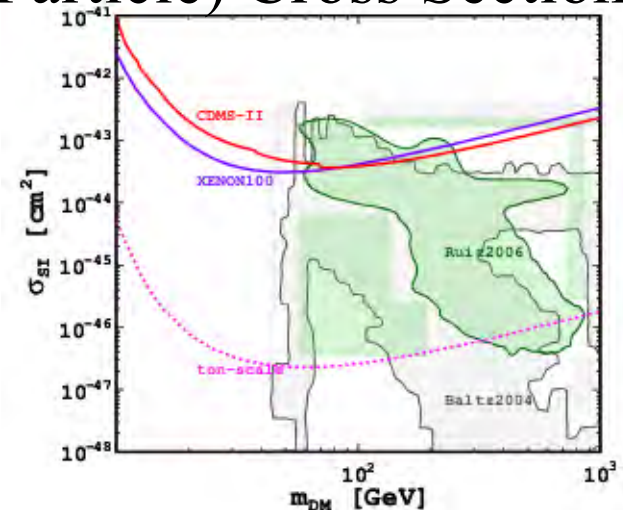
Neutrino Sources at FNAL

- We can use neutrinos from the Booster Neutrino Beam (BNB).

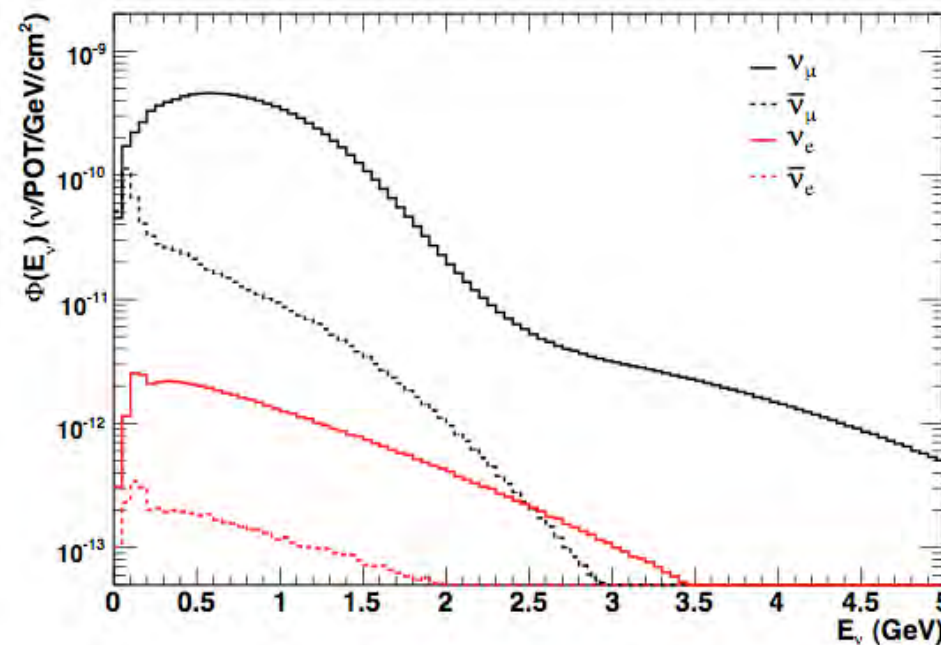- BNB is an existing neutrino source previously used for the MiniBooNe experiment.

Proposed detector site at FNAL
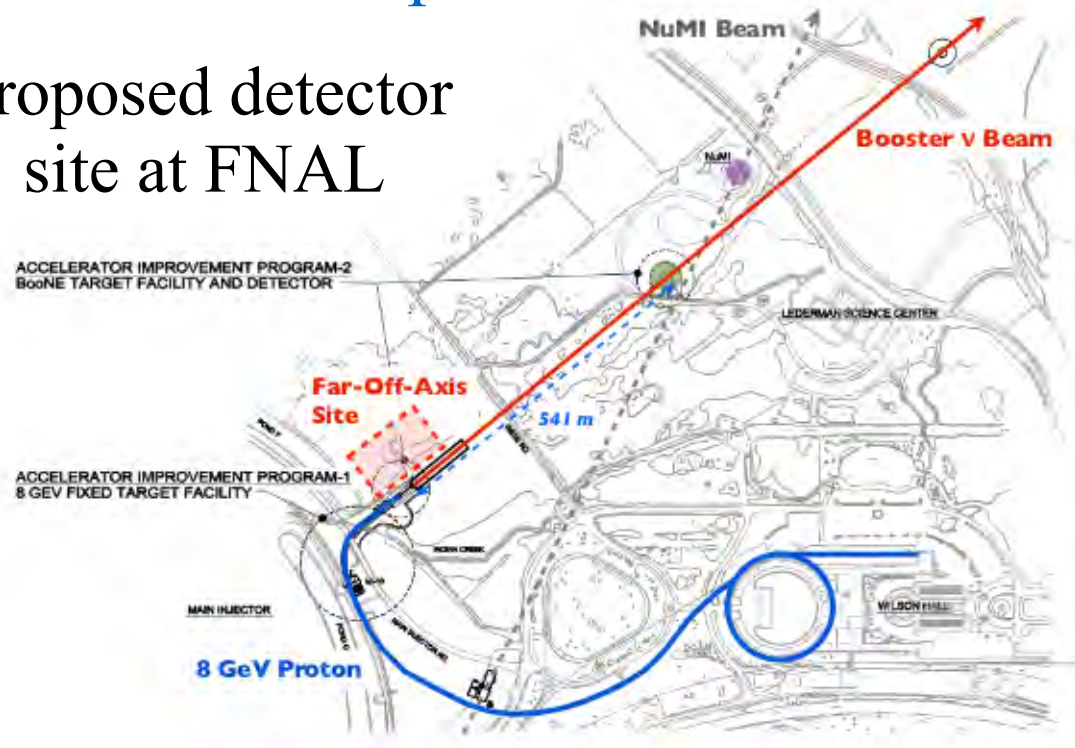
- Uses Booster synchrotron proton source to generate π^+, which decay into μ^+ and ν_μ

Neutrino Sources at FNAL

▶ On-axis neutrinos from the BNB are in the GeV energy range, too energetic for coherent-NCνAS.
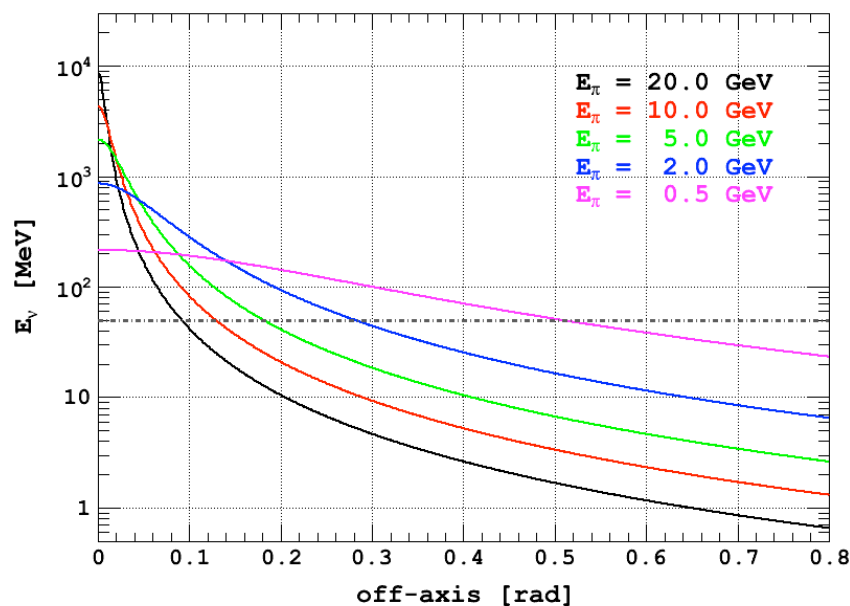

On-axis neutrino flux prediction at MiniBooNe detector site (arXiv:0806.1449)
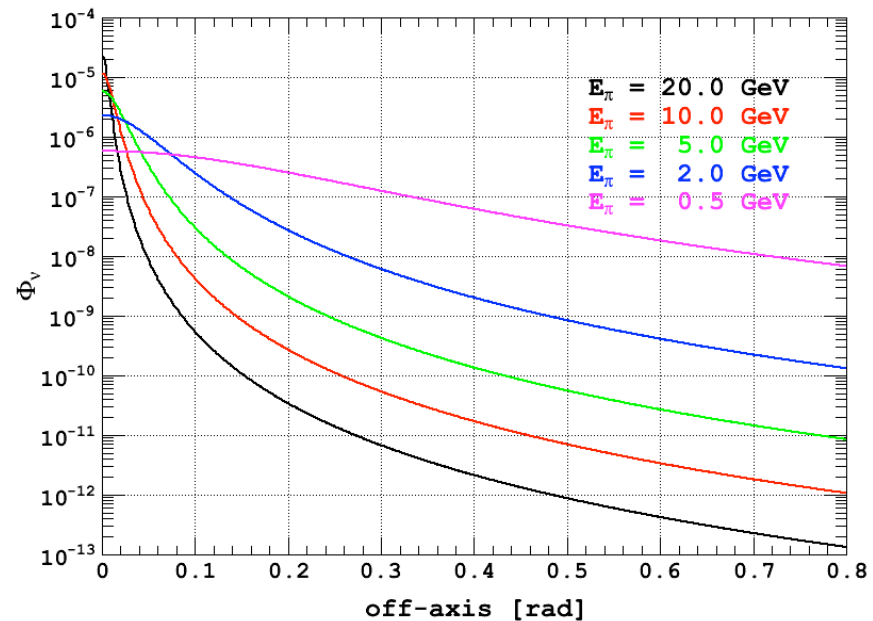
Neutrino Sources at FNAL

▶ The solution is to utilize far off-axis neutrinos.

The energy of the neutrinos is lower (MeV range) and the distribution is narrower.

Off-axis neutrino energy
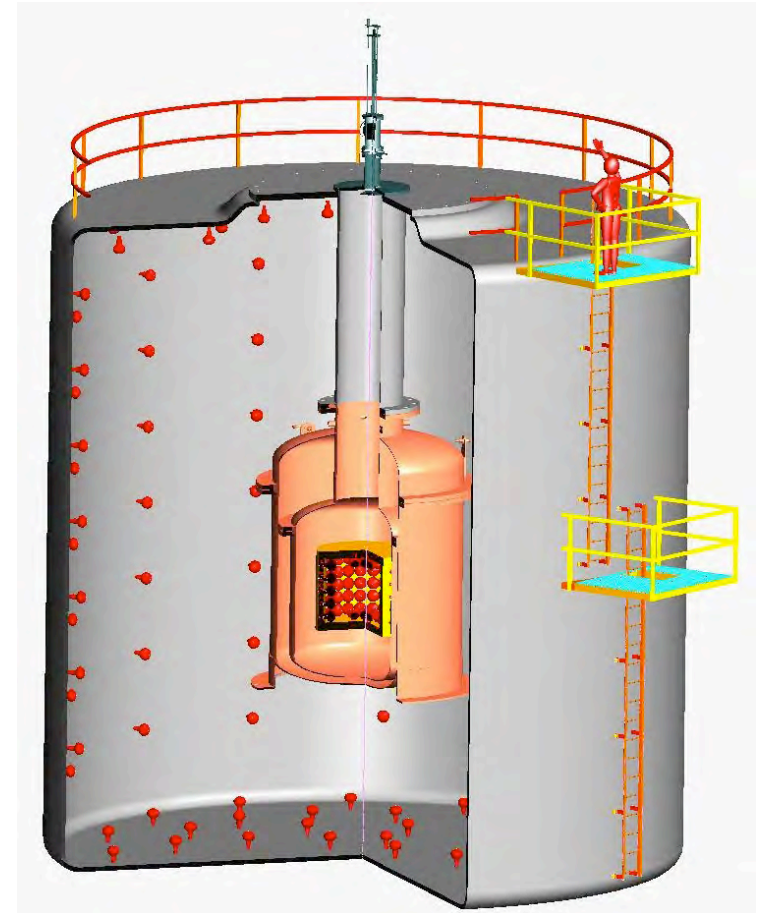

Off-axis neutrino flux

Liquid Argon Detector
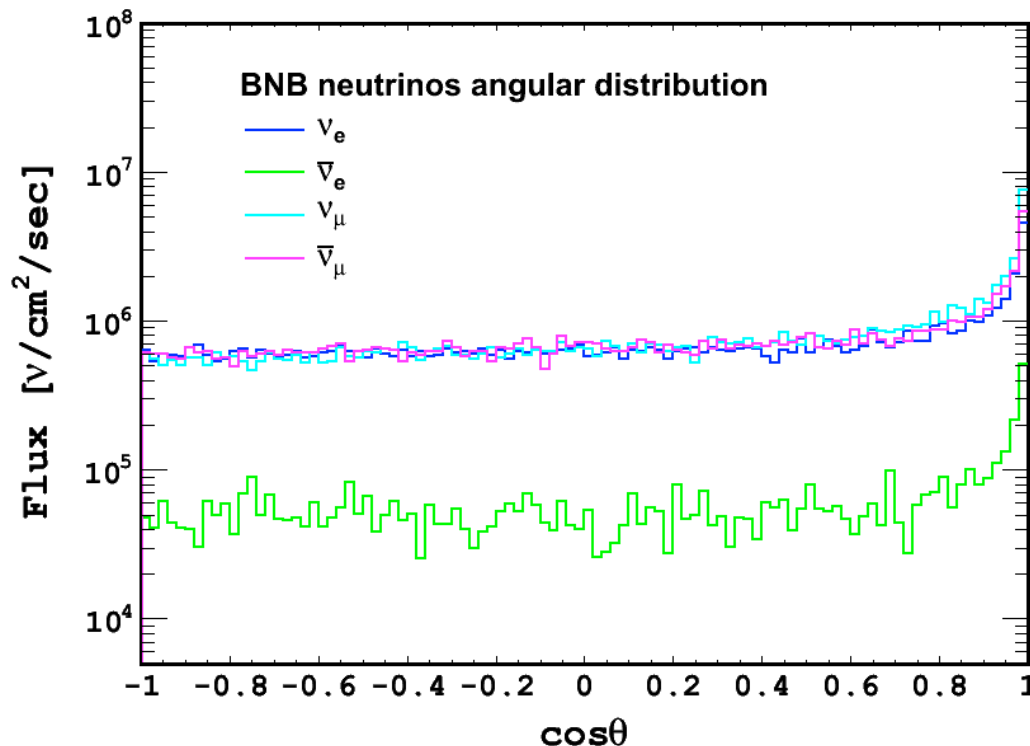
▶ The detector would use liquid Argon (A = 40, Z = 18).

Ar is a strong scintillator with ~40 photons/keV and is transparent to its own scintillation light.

▶ Electron and nuclear recoils can be distinguished.

The singlet and triplet decays have different populations in electron and nuclear excitations, leading to different pulse shapes.

Liquid Argon Detector

Flux prediction for off-axis
neutrinos from BNB Monte
Carlo

▶ A large detector mass is
needed to produce
enough events.

With a ton-scale detector
and a flux of $\sim 5 \times 10^5$ ν/
cm^2/sec, we expect
~ 200 events per year.

Neutron Backgrounds

▶ Neutron backgrounds present a problem, since coherent elastic neutron scattering events in the detector volume may mimic the signature of coherent-NCvAS events.

In Ar-40, coherent neutron scattering has a cross-section of 4.21×10^{-25} cm^2 (from NIST database).

14 orders of magnitude higher than coherent-NCvAS!

▶ Backgrounds which are not correlated with BNB operation can be rejected by using a small detector time window and beam-off background subtraction.

Beam correlated neutrons are still a problem.

Neutron Backgrounds

- To further reduce the neutron background, radiation shielding is necessary.

  Empircally, we know that H has a large neutron scattering cross section.

- Water (~11% H by weight) is thus a good neutron shield material.

  Design of liquid argon detector includes outer tank of water for muon veto and neutron shielding.

  However, depending on the actual levels of background radiation, further shielding may be needed.

Monte Carlo Simulation

▶ A toy model was developed that can be used to estimate the amount of shielding necessary.

For initial studies, effects from the geometry are not as important.

▶ The Geant4 (GEometry ANd Tracking) Monte Carlo toolkit was used to simulate the neutron background.

▶ Geant4 is an object-oriented (C++) framework for simulating particle interactions, developed by the Geant4 Collaboration and maintained by CERN.

Simulation Geometry

▶ Simplified geometries were employed to facilitate the determination of the effectiveness of concrete as a shield for neutron radiation.
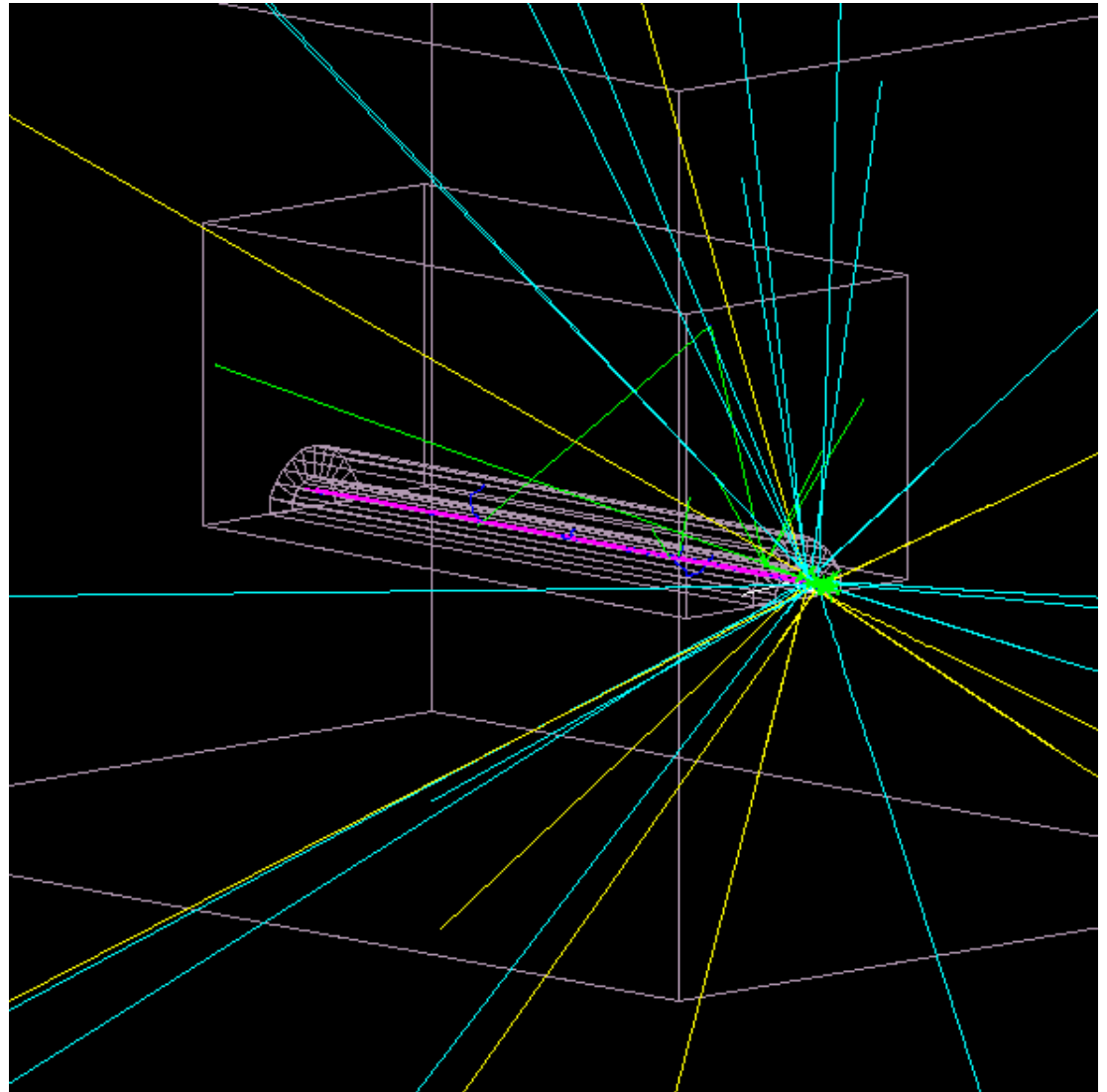
Simulation Geometry
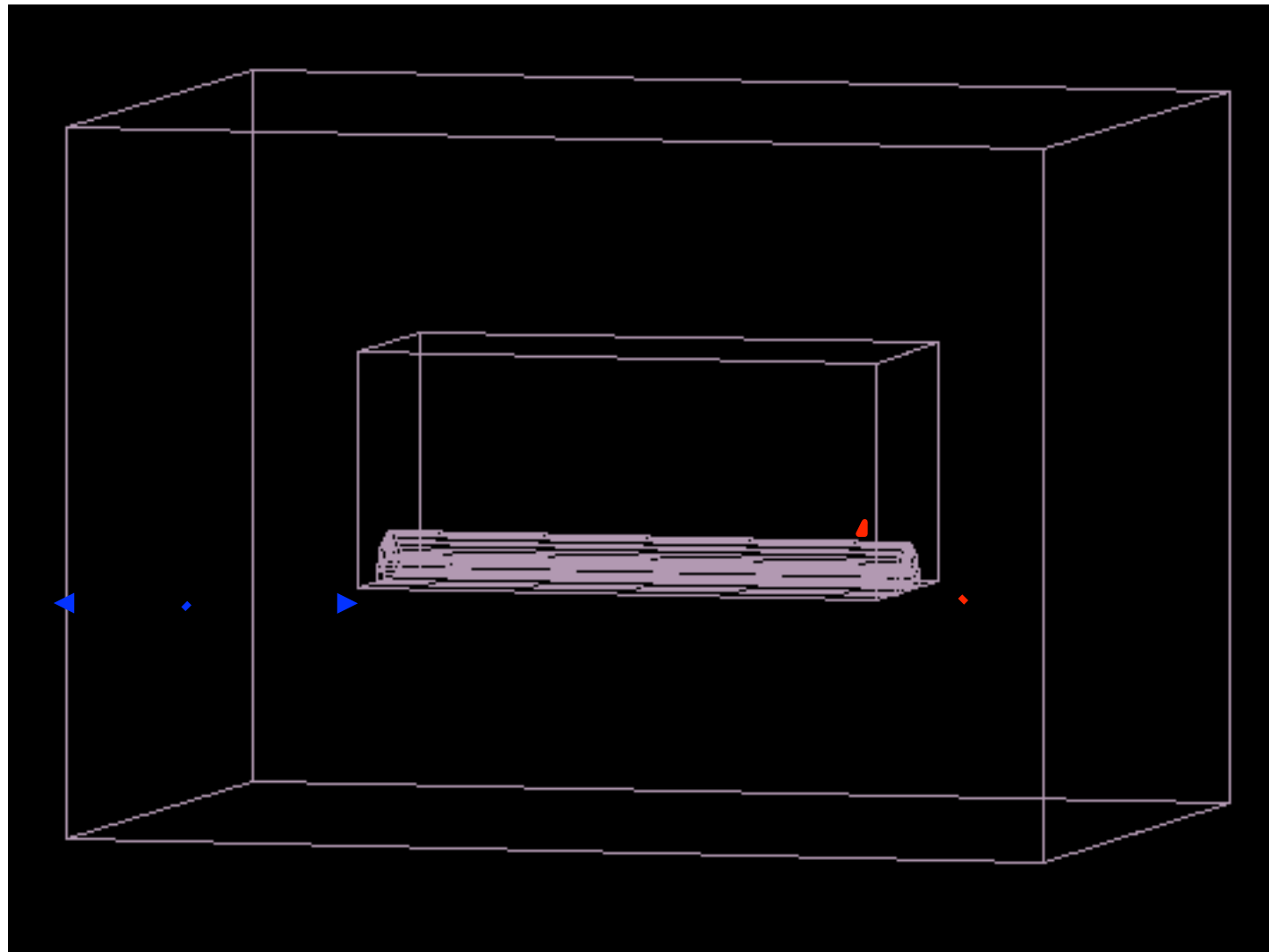
Attenuation
Area

Particle
Source

Simulation Details

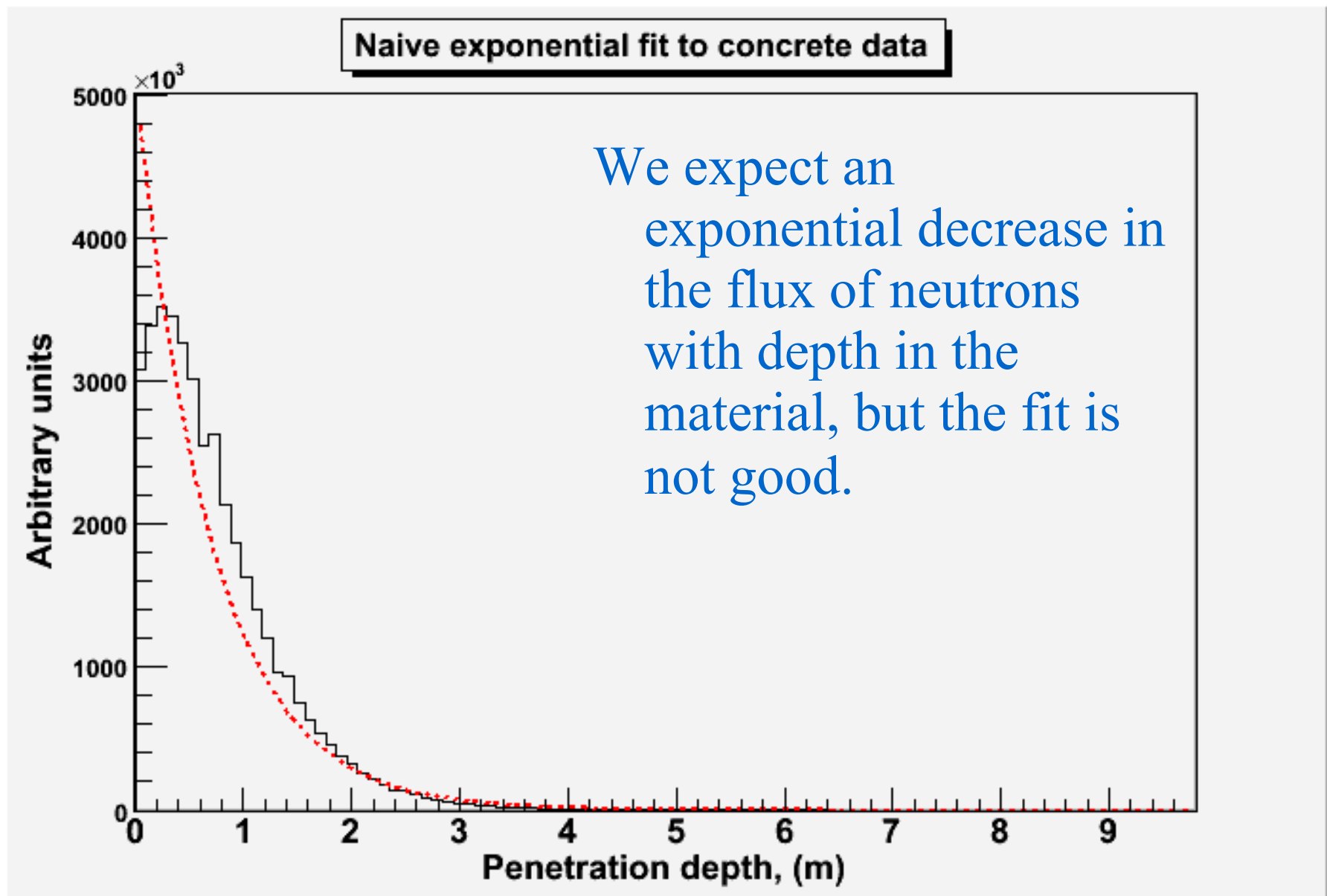▶ In this initial simulation, an idealized beam of neutrons was modeled.

Circular beam profile, 1 sigma radius = 5 cm

Beam energy: 1.0±0.1 GeV

By default, the primaries were neutrons, but the simulation can handle other particles.

▶ The identities, energies, and momenta of the particles in the simulation were recorded as they traveled through a 20 m thick concrete barrier.

Results

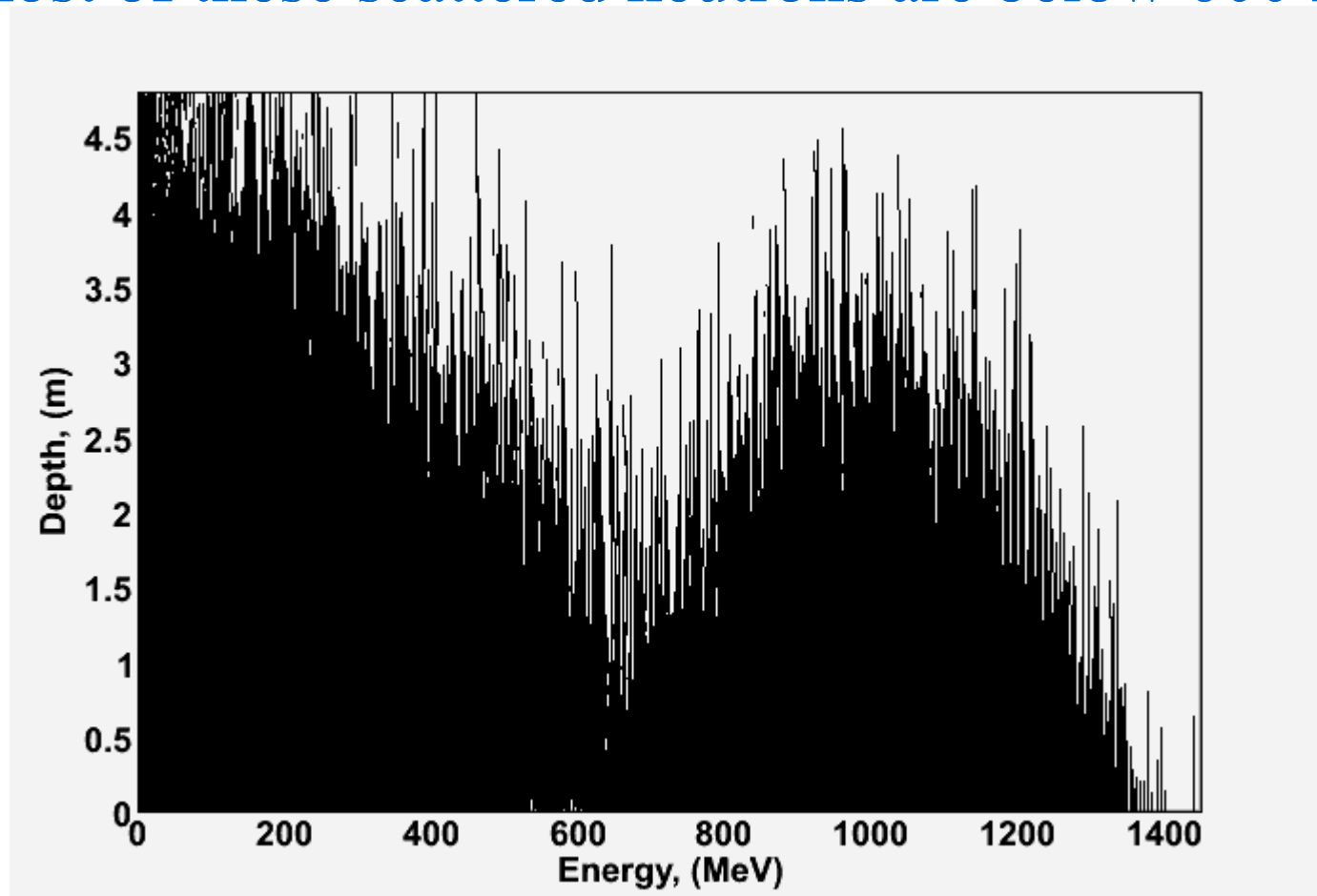We expect an exponential decrease in the flux of neutrons with depth in the material, but the fit is not good.

Results

▶ The distribution is skewed by low-energy neutrons scattered into the target area by the geometry or produced in collisions with nuclei in the material.
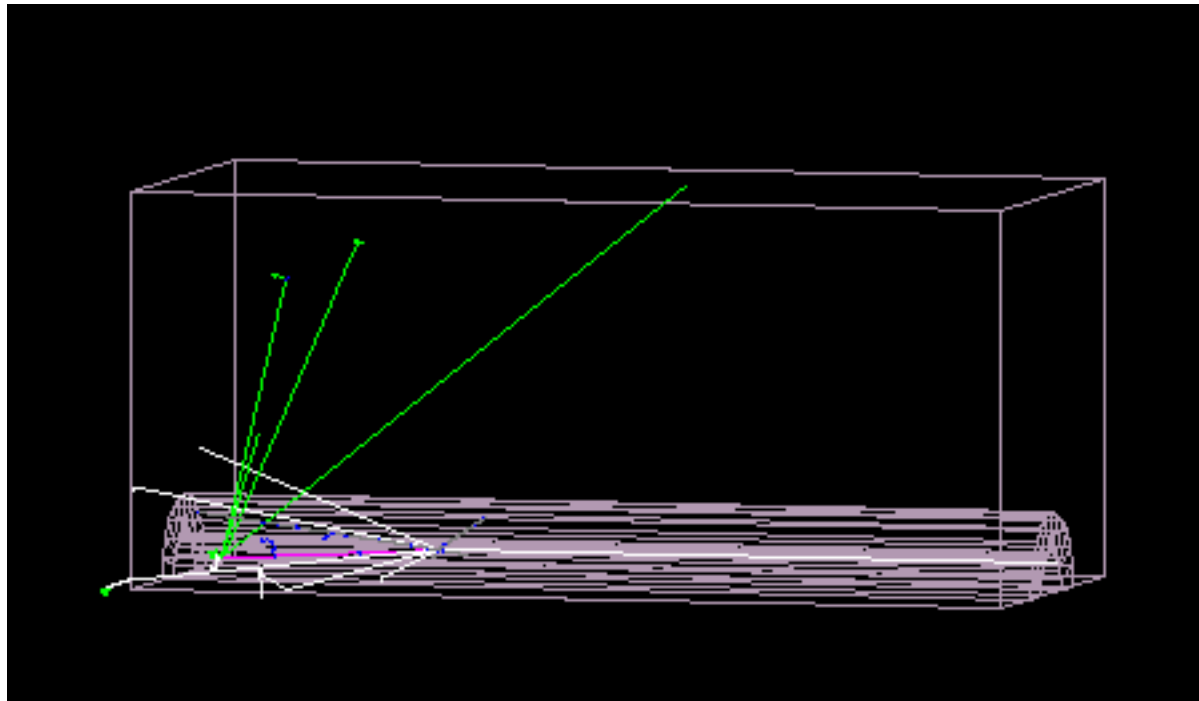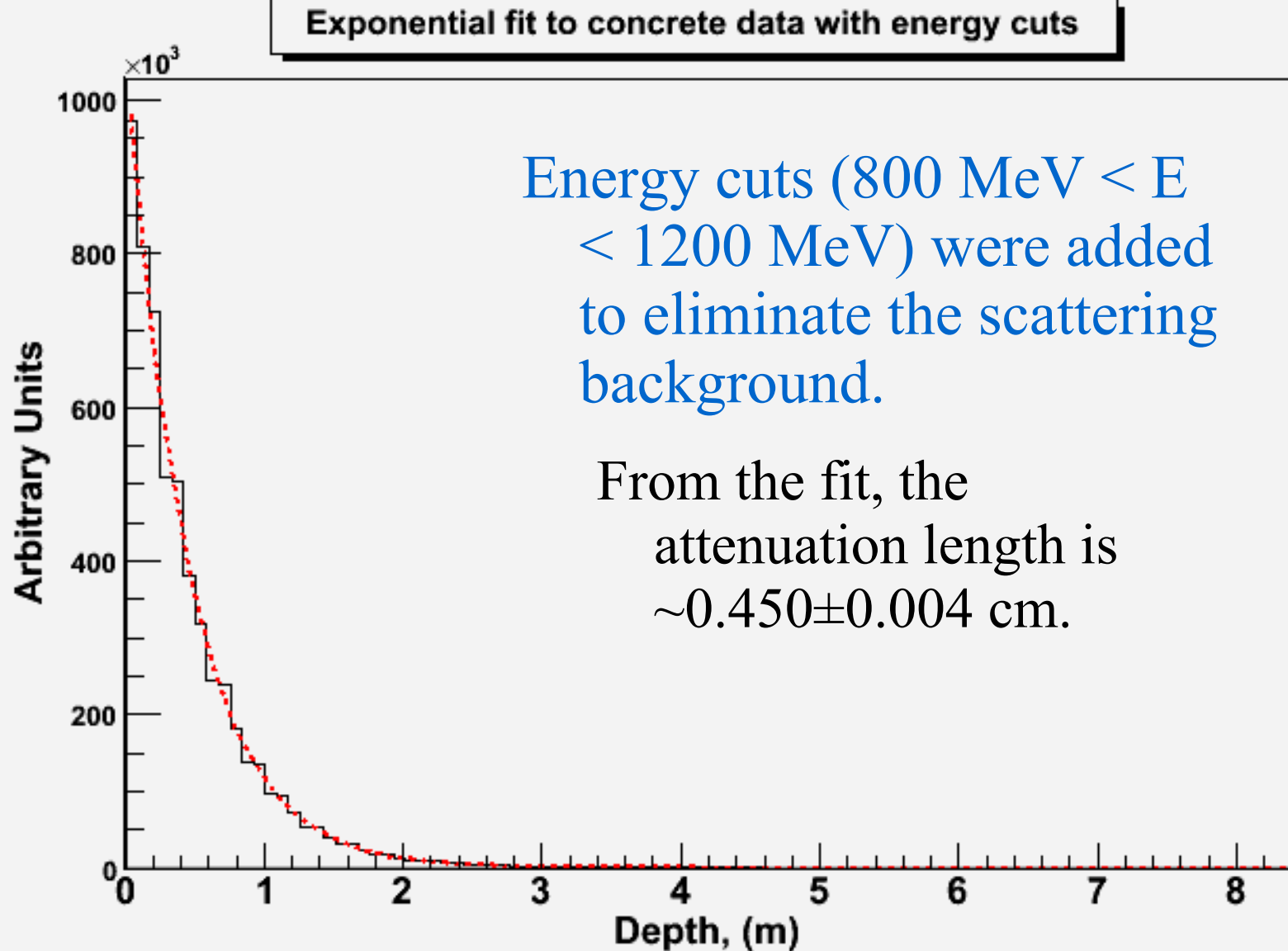
Results

▶ Plot of distribution in energy-depth parameter space shows that most of these scattered neutrons are below 600 MeV.

Results

Exponential fit to concrete data with energy cuts

Energy cuts (800 MeV < E < 1200 MeV) were added to eliminate the scattering background.

From the fit, the attenuation length is ~0.450±0.004 cm.

Conclusions and Future Directions

▶ The toy model simulation developed will be useful in estimating the amount of shielding necessary for the proposed experiment.

Simulation with full geometry is computationally expensive, but the toy model can suggest which regions of parameter space to investigate.

▶ The program can be extended for more detailed simulations in the future.

Include more realistic beam-flux and compare different shielding materials.

References

[1] Freedman, Daniel Z., "Coherent Effects of a Weak Neutral Current." *Phys. Rev. D* 9, no. 5 (1974): 1389-92.

[2] Wilson, James R. "Coherent Neutrino Scattering and Stellar Collapse." *Phys. Rev. Lett.* 32, no. 15 (1974): 849-52.